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Unveiling correlations between transient tunnel deformations and in-situ geomechanical parameters derived from tunnel seismic data

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Abstract: Hard rock tunnelling is a unique endeavour that requires close collaboration among various disciplines, including civil engineering, geotechnics, geology, and geophysics. In modern tunnelling projects, diverse types of data are continuously collected by instruments and personnel across these fields. Typically, these datasets are analysed within each discipline separately, and due to time constraints, comprehensive interdisciplinary evaluations are rarely conducted. Beyond standard descriptive parameters—such as those provided by rock mass classification systems and convergence measurements—seismic velocities obtained from Tunnel Seismic Prediction methods are of particular interest. Tunnel seismic is carried out during the excavation phase by placing seismic sensors and generating waves in boreholes using small explosive charges near the tunnel face. From the estimated wave velocities, geomechanical parameters such as the dynamic Young's modulus can be derived. These seismic surveys typically allow predictions up to 150 meters ahead of the tunnel face. In this work, results from approximately twenty seismic surveys conducted at the longest road tunnel ever constructed in Latin America are validated using geological face mapping. Subsequently, a detailed evaluation of the geomechanical parameters and convergence measurements collected along the same segments as the seismic data revealed breakthrough correlations between the datasets. Based on these analyses, unique look-up tables, helpful for future surveys and for risk management, were developed that integrate rock support types, elastic modulus, and maximum accumulated deformation.

Keywords: Geological uncertainty; tunnel seismic; deformation; geomechanical parameters

1. Introduction

Thanks to advancements in excavation techniques over the past two decades, hard rock tunneling projects are now executed at greater depths and involve increasingly longer tunnel alignments. Simultaneously, the proliferation of sensors, monitoring technologies, exploration methods, and digital data storage has enabled the collection of a wide variety of multi-source datasets (Apoji et al., 2023).

Among the diverse datasets typically collected across various disciplines are geological data such as face logs, probe drill logs, and discontinuity mapping; geotechnical data including deformation monitoring, convergence measurements, and both in-situ and laboratory-based strength data; geophysical data comprising tunnel seismic surveys, resistivity measurements, and borehole ground-penetrating radar (GPR); and excavation-related data such as Measurements While Drilling (MWD) and Tunnel Boring Machine (TBM) performance parameters.

During excavation, geological and geotechnical data are evaluated by site geologists and geotechnical engineers. While these analyses may often be conducted independently, in the best scenario at least one project member has interdisciplinary knowledge or background bridging both domains. A key output of this process is the rock mass classification, typically updated after each production cycle and integrated into the evolving geological model. Furthermore, monitoring networks for deformation and convergence of the tunnel surface or lining are increasingly implemented in tunnelling projects. These systems enable the collection of time-dependent data, which reflect the rock mass's response to

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excavation. Such data serve as valuable indicators of rock mass behaviour and stress redistribution due to material removal, as well as the interaction between ground and support structures (Kaiser and Korpach, 1986).

Tunnel Seismic Prediction (TSP) is a geophysical technique specifically developed for hard rock tunnelling which helps to minimise the risks associated to poor rock mass conditions (Dickmann and Krueger, 2014). By using 4 sensors installed into the tunnel walls, seismic waves generated using explosives charges or an impact source are recorded and evaluated. The technology aims at detecting geological structures such as: fault and shear zones, fractures/jointed zones, presence of cavities, etc. It stands out due to its rapidness for data acquisition and processing, achievable prediction range (up to 150 metres or more) and high accuracy.

Each of the aforementioned techniques provides critical information for the tunnel engineer's decision-making process in areas such as excavation performance, support design, and alignment adjustments. More importantly, this geo-information is vital for mitigating geological risks. However, a common shortcoming is the limited interdisciplinary evaluation of these datasets, a gap that can be attributed to the time-consuming nature of data integration and analysis across domains.

In this work, we present an integrated analysis of geological face mappings, convergence measurements, and tunnel seismic data collected from a road tunnel project in the Colombian Andes. At the moment of this study, approximately 2,590 meters of tunnel were covered by 20 seismic campaigns. Seismic predictions were carefully compared against Rock Mass Rating (RMR) values and convergence measurements, with the aim of evaluating the consistency and predictive value of the seismic data. Moreover, despite the differing nature of the data sources, and assuming that each dataset directly or indirectly reflects the physical properties of the rock mass, an important objective of this study was to explore potential correlations between them.

2. Fundamentals

2.1. Convergence in tunneling

Convergence in tunneling refers to the radial closure of the tunnel section in time due to the stresses excerpt by the surrounding rock mass and the excavation itself. Depending on the rock mass type and condition, tunnel convergence may result in either reduction of the section or collapses (Kontogianni and Stiros, 2003). Commonly, tunnel convergence occurs near the excavation face and it can be interpreted as a response of the ground due to the gradual rearrangement of stress around the opening. Generally, it can be inferred that convergence in weak rock masses with low compressive strength tends to be greater than in competent rock masses with higher compressive strength. Moreover, the presence of large fault and intense jointing or fracturing may influence the degree of deformation (Kim et al, 2005). Consequently, it can be assumed that the elastic modulus should be rather low at zones prone to high deformation.

In modern tunneling, convergence measurements can be considered as a standard. Hence, there are a number of instruments and methods for measuring tunnel deformation, tape extensometers being the most traditional common one. Tape extensometers measure relative displacement of the tunnel periphery at fixed point locations. The main importance of measuring tunnel convergence is that it helps on understanding the rock mass behavior at the predefined geotechnical units throughout the tunnel alignment. Therefore, it contributes to the decision-making process for the most suitable and economic rock support to be used at each section.

2.2. Tunnel Seismic Prediction

TSP is a method widely used in hard rock tunneling. It relies on reflection seismic and allows to estimate the velocity of the P-waves (longitudinal waves) and S-waves (shear waves) directly from data recorded behind the tunnel face. In its standard application 24 shot holes (or shot point when using impact sources) are prepared and blasted using small explosive charges. The shot holes are placed as close as possible to the tunnel face (Fig. 1).

Fig. 1. Standard layout when using the TSP 303 technology consisting of an array of 24 shot points and four 3-component receivers are installed as close as possible to the tunnel face.

The downtime needed for data recording can be as short as 15 to 30 minutes and results can be delivered within few hours after data acquisition. The processing involves a number of steps for preparing and evaluating the seismic data, i.e. the seismic traces, before going into a numerical modeling. By meanings of 3D velocity analyses and depth migration, zones featuring high reflections ahead of the face are illuminated (located) in space resulting in so-called reflectors. The most significant reflectors are automatically extracted by the software accompanying the system. According to their spatial position along each velocity field, each reflector has velocity values for P- and S-waves and the corresponding elastic or geomechancial parameters. The parameters dynamic Young's modulus (*Edyn*), Poisson ratio (v), shear modulus (μ) and Bulk modulus (K) are calculated from the estimated seismic velocities assuming a representative density value for typical rock types.

Variations in the velocity values and the geomechanical parameters between consecutive reflectors form the basis for drawing conclusions about the changes in rock mass conditions ahead of the face. For instance, decreasing the value of *Edyn* is a good indicator of decreased rock stiffness due to the presence of a weakness zone. As the spatial position and orientation of each reflector is estimated, these changes are projected onto the tunnel axis. The latter is also an input to the system's software, which uses the same project coordinates. The prediction of the rock mass state is thus included in the metrics used in the project.

3. Project location and description

The Guillermo Gaviria Echeverri Tunnel and its access roads Megaproject is a road project located at the western part of the Antioquia Department, Colombia (Fig. 2). Along with several other structures, it comprises the construction of the 9.7 km tunnel, also referred to as the Toyo Tunnel. The project belongs to the Proyecto Autopistas de la Prosperidad which is part of the National Government Program Fourth Generation Roads 4G and it is executed as a public work led by the regional government. The project will connect two other key road projects, the concessions Mar 1 (Medellin – Santa Fé de

Antioquia) and Mar 2 (Cañasgordas – El Tigre), all of them aiming at connecting production centres located within the Antioquia Department, the country middle region and the Pacific and Atlantic coasts. The tunnel was built by the Antioquia al Mar Joint Venture (CAM). It comprises the excavation of a main tunnel and an escape gallery being excavated with two opposite headings (Entry and Exit Portals).

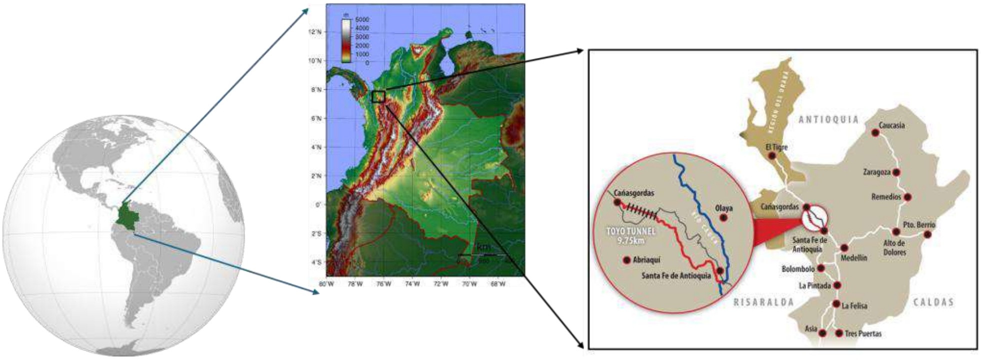

Fig. 2. Location of the Megaproject Guillermo Gaviria Echeverri Tunnel and its access roads (right: Modified from FCC Construction).

3.1. Local Geology

Local geology along the tunnel alignment comprises sedimentary and igneous rocks of two formations: Penderisco and Barroso. The first formation includes thin layers of shales, siltstone, mudstone and lydite occasionally interbedded by volcanic rock packages (basalt and diabase) while the second comprises basalts, gabbro, diabase, andesites and volcanic tuff. According to the geological forecast, a number of fault zones and intrusions are expected along the transect (Fig. 3). Likewise, predicted RMR values range between 20 and 80 indicating a high variability of the rock mass condition along the almost 10 km transept to be crossed. The overburden varies from a few meters around portal area up to about 900 m in the middle of the tunnel.

The geology after excavation along the areas where tunnel seismic results were available present two different rock mass conditions. Along the Entry Portal (EP), the Barroso Formation is found while at the Exit Portal (OP) the Penderisco Formation dominates, the boundary of both formations is located approximately at the middle of the tunnel alignment. At the EP, the geology is predominantly diabase rocks (dolerite) and basalts of moderate to high strength with moderate fracturing. At the OP, lithology is dominated by a sequence of sedimentary (siltstone, mudstone, shales) and volcanic rock (basalt). According to site geologists and face mappings, predominantly sequences of siltstone and shale are present characterised by low to moderate strength, moderate alteration, tectonised, high degree of fractures and folding evidence.

4. Methodology

4.1. Data collection

Seismic and geological results were collected in separated databases. Results coming from 17 seismic campaigns, 10 and 7 at the EP and OP, respectively, were analysed. Geological information is available in form of spreadsheet. Inputs of the spreadsheets contain information gathered from the geological face mappings after each blast. Deformation measurements were performed using 5 convergence points placed about every 15 metres along most of the alignment, only at weakness zones, e.g. rock type 4 and 5, distance was in average 5 metres. The measuring points were situated symmetrically as shown in Fig. 4. After a given blast, recordings of deformation were done daily at stations near the face. For the remainder stations, the recordings were either weekly, biweekly or monthly, depending on the response of the rock mass to the rock support. The stop criterion was when deformations were at maximum 2 mm/d. The recordings are available in spreadsheets. Table 1 shows the main parameters obtained from each investigation method. Table 2 shows basic descriptive values of the parameter used for the validation and further analyses. All TSP related parameters are calculated as well as the RMR. The accumulated deformations were measured.

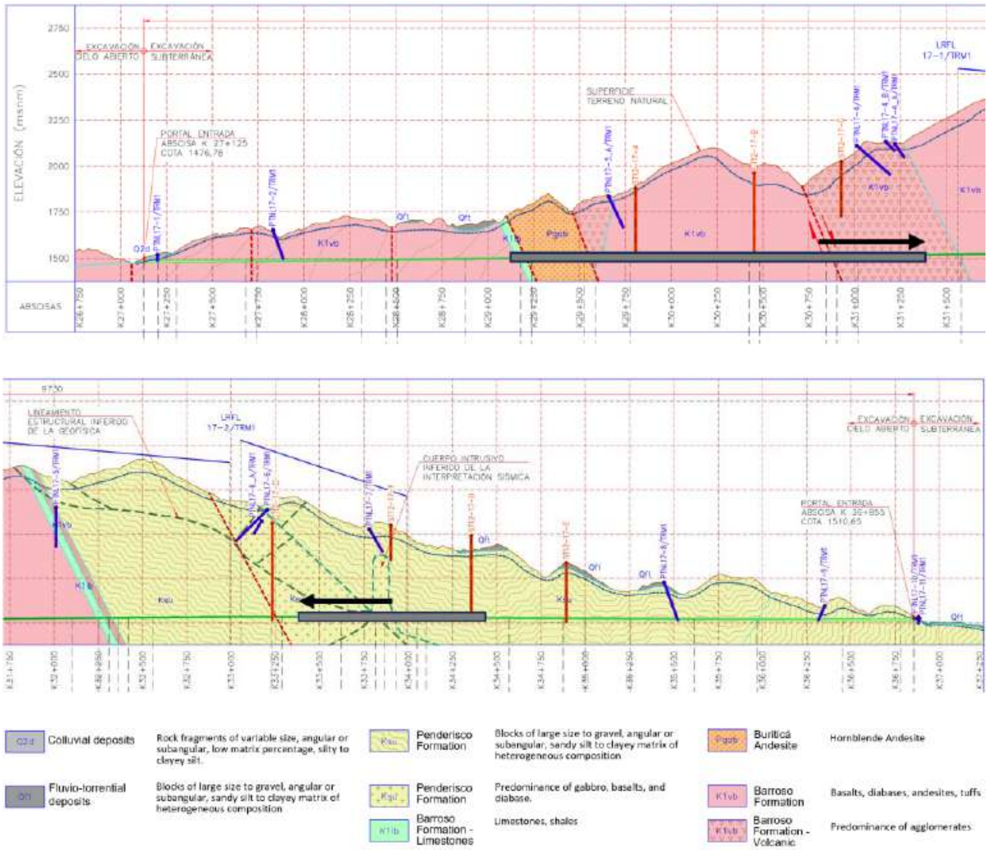

Fig. 3. Geological longitudinal section showing the main two type of rock formations: Barroso and Penderisco, pink and yellow, respectively. The tunnel sections covered by the seismic campaigns analysed in this study till 2021 are indicated by the grey box upon the tunnel alignment. Headings directions are also indicated, upper corresponding to the Entry Portal (EP) and bottom to the Exit Portal (OP).

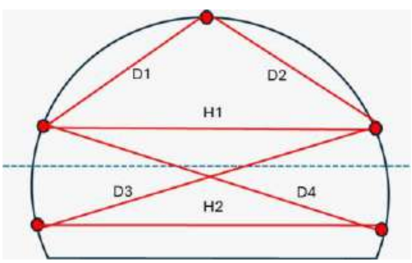

Fig. 4. Schema showing the strings measured for monitoring the tunnel convergences. In this study the strings H1 and H2 were used.

Table 1. List of parameters obtained by each investigation method.

Method	TSP	Face mapping	Extensometers
Parameter	TM: Tunnelmeter [m]	TM: Tunnelmeter [m]	TM: Tunnelmeter [m]
	V_p: P-wave velocity [m/s]	RQD: Rock Quality Design	D_{acc}: Accumulated deformation [cm]
	V_s: S-wave velocity [m/s]	RMR: Rock Mass Rating	
	ν: Poisson coefficient [-]	RS: Rock Support	
	E_{stat}: Static Young's mod. [GPa]	Lit: Lithology	
	E_{dyn}: Dyn. Young's mod. [GPa]	FD: Fracturing degree	
	μ: Shear mod. [GPa]	WP: Water presence	
	K: Bulk mod. [GPa]	WA: Weathering/Alteration	

Table 2. Relevant parameter values as used for the analyses.

	Entry Portal				Exit Portal			
Parameter	Samples	Minimum	Maximum	Median	Samples	Minimum	Maximum	Median
V_p		3,170	5,675	4,605		3,440	5,500	4,225
V_s	161	1,900	3,160	2,660	119	1,840	2,770	2,420
E_{dyn}		20	70	45		21	50	32
RMR	341	18	74	45	299	16	56	37
D_{acc}	114	0.53	41.10	5.71	95	0.87	48.53	12.23

4.2. Data preparation

The spatial location of each parameter was referred to Tunnelmeter (chainage) of the project. Parameters laying within a range of 2 m from each other were used for each evaluation. Tunnel seismic results were carefully validated according to both the Rock Mass Rating (RMR) estimated at a given position and the geological description as presented in the face mappings for that location. In this qualitative evaluation, the closest values to a given position were compared considering the overall trends within a section.

In general, most of the seismic results were in good agreement with the RMR trends and the rock mass condition experienced along the prediction range. In only 2 cases, a reprocessing of seismic data was necessary, mostly due to campaigns performed at zones where the seismic layout was laying along weakness zones posing a challenge for estimating important reference parameters. After calibrating the processing parameters (mostly initial velocity for the seismic modeling), seismic results along zones of concern were in good to very good agreement with the geological parameters. Once the validation of the seismic results was finished, each individual parameter coming from the seismic was plotted against the maximum accumulated deformation. Again, the closest sample position was selected. Final results are presented as graphs unveiling important correlations between them.

5. Results

Fig. 5 shows *Edyn* calculated from seismic data versus RMR values for EP. The top graph shows the rock support as build, being 1: very light rock support to 5: very heavy rock support. *Edyn* curves from each individual TSP campaign can be easily identify since there was no overlap between campaigns. Some gaps were due to lack of seismic results. Special care must be taken when comparing *Edyn* and RMR values. Considering the nature of each data, a one-to-one comparison or analysis using simple statistics must be misleading. Instead, it is recommended to perform a qualitative analysis by observing overall trends and value changes within and between campaigns.

As can be seen, similar trends between *Edyn* and RMR are present in each campaign and throughout the investigated tunnel transept. Increasing *Edyn* values are in very good agreement with high RMR and vice versa with values ranging between 20 GPa and about 70 GPa (average 43 GPa). The estimated values indicated a moderate rock mass condition along most of the investigated area with high variability, showing good rock mass conditions at some areas, e.g. TSP#6, and poor rock mass at other locations, e.g. TSP#9 and TSP#10. For zones having low RMR (M 24+510 to 24+570, TM 29+990 to

30+060 and TM 30+330 to 30+470), the seismic results are either at the far end of the predictions or there isn't value since no seismic measurement was performed. Nevertheless, the *Edyn* towards the end of the prediction of campaigns TSP#3, TSP#7 and TSP#8, and those of the following campaigns (TSP#4, TSP#7, TSP#8, TSP#9 and TSP#10), resemble the low RMR or less competent rock mass conditions along these zones. In term of geological structures, the first zone with low *Edyn* and RMR corresponds to a highly fracture zone which actually represented the fault observed in the geological model, expected ahead of the actual location (See Fig. 3). The second zone with low values towards the end of the evaluated area, are due to the presence of a dioritic intrusion and the contacts with the diabase formation.

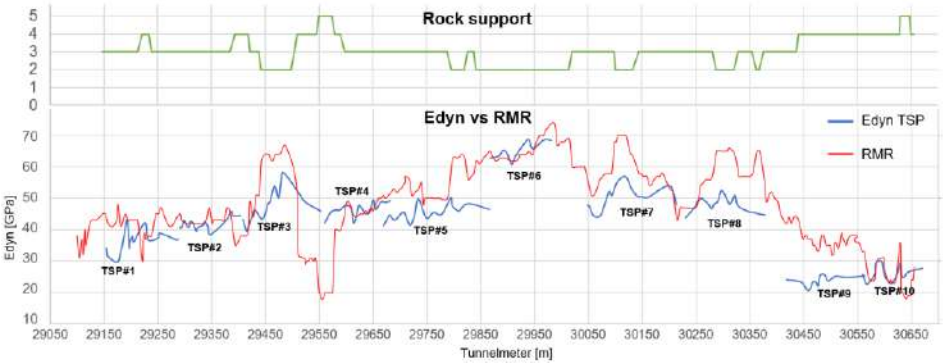

Fig. 5. *Edyn* vs RMR values for the Entry Portal (EP). The top figure shows the type of rock support employed (1: light rock support for favorable rock mass, 5: heavy rock support for very poor rock mass).

Selection and changes of the rock support while excavation was supported by the geological characterization (RMR values obtained) and also by the results of the convergence measurements near the face. Notice that at sections were low RMR values were estimated, rock support was changed to 4 and 5. It is important to mention that around TM 29+520 and TM 29+560, the highest accumulated deformations were measured, leading to an immediate change in the rock support (from 2 to 4, personal communication from site geologists). Similar situation occurred from TM 30+400 onwards. Regarding the elastic parameters, it can be observed that at sections where rock support 2 and 3 were used, the values for *Edyn* were > 50 GPa and *Edyn* > 40, respectively. At sections were rock support 4 and 5 was applied, decreasing *Edyn* values or lowest *Edyn* were estimated.

Fig. 6 shows *Edyn* calculated from seismic data versus RMR values for OP. The top graph shows the rock support as build. As in the opposite portal, *Edyn* curves from each individual TSP campaign can be easily identify since there was no overlap between campaigns.

As can be seen, similar trends between *Edyn* and RMR are present in each campaign and along the investigated transept. Increasing *Edyn* values are also in very good agreement with high RMR and vice versa with values ranging between 21 GPa and 50 GPa (average 34 GPa). In most campaigns, *Edyn* values follow to good precision local changes within short sections. Contrary to the result at PE, all parameters showed lower values at this heading as expected due to the predominant rock types of the Penderisco Formation. In addition, the rock mass condition itself was very poor to poor since the beginning of excavation at this portal.

At sections with RMR ranging between 40 and 60 (*Edyn* within 35 and 50), rock support 3 was applied (most of the section). Rock support 4 and 5 were employed at sections with lower RMR or high deformation, TM 33+580 to TM 33+660, TM 33+860 to TM 33+870, TM 33+900 to TM 33+915 and from TM 34+210 to TM 34+400. Along most of these weaker sections, *Edyn* values lower than 25 GPa were estimated. Only at TSP#4, those changes could not be identified by any reflector, likely due to a spatial resolution limitation.

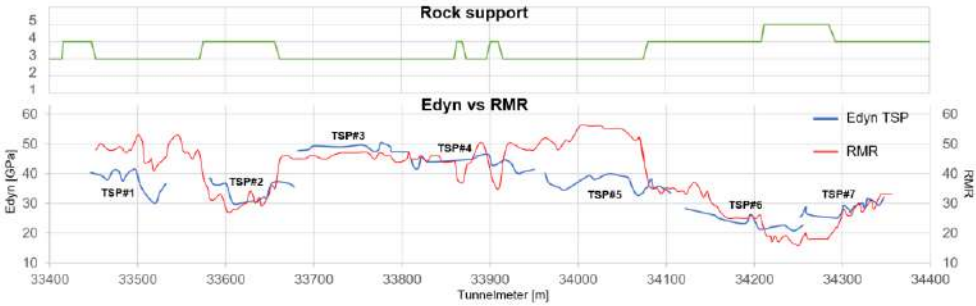

Fig. 6. *Edyn* vs RMR values for the Exit Portal (OP). The top figure shows the type of rock support employed (1: light rock support for favorable rock mass, 5: heavy rock support for very poor rock mass).

In addition to the above-mentioned validation and evaluation of seismic, *Edyn* values were plotted against maximum accumulated deformation as measured along the tunnel transept using tape extensometers (Fig. 7). Only the upper string (H1) was used since it showed the larger convergence values and variability compared to H2. The figures allow a simple verification of the *Edyn* areas for which a certain deformation is to be expected. By adding the type of support, additional conclusions can be drawn about the relationship between *Edyn*, the accumulated deformation and the selected support.

It is important to mention that prior to the elaboration of these figures, the relationship between overburden and deformation was scrutinized. For both headings, a positive correlation, i.e. larger convergence due to increasing overburden was not clearly identified. In EP, the largest convergences were measured at zones with lowest overburden or at sections where the overburden has a negative gradient. Similarly, in OP heading, even a negative correlation is observed, i.e. convergences were slightly higher as the overburden increased. Based on the correlations, the following main conclusions can be drawn per portal:

Entry Portal (EP)

- *Edyn* range: 20 – 30. Highest deformation possible, up to ca. 30 cm. RS 4 is used predominantly. RS 5 in punctual cases to control instantaneous deformations > 10 cm.
- *Edyn* range: 30 – 40. Low deformations, < 10 cm. RS 4 is used predominantly.
- *Edyn* range: 40 – 50. Low to high deformations, up to around 30 cm. RS 3 is used predominantly. RS 4 and 5 used in punctual cases to control instantaneous deformations > 10 cm.
- *Edyn* range: 50 – 70. Very low deformations, < 6 cm. Rock support 2 is used predominantly

Exit Portal (OP)

- *Edyn* range: 20 – 30. Highest deformation possible, up to around 50 cm.
- *Edyn* < 26, RS 5 is used predominantly, otherwise RS 4.
- *Edyn* range: 30 – 40. Still high deformation possible, up to around 40 cm.
- *Edyn* < 35, RS 4 is used predominantly, otherwise RS 3.
- *Edyn* range: 40 – 50. Moderate deformations, up to around 20 cm.
- RS 3 is used predominantly. RS 4 only in punctual cases to control instantaneous deformations > 10 cm.

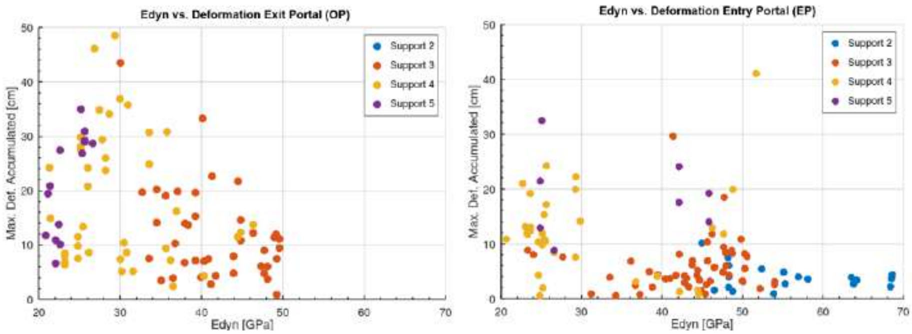

Fig. 7. Plots of *Edyn* versus maximum accumulated deformation including primary rock support as built. Left: Exit Portal, right: Entry Portal.

Table 3 and 4 present basic statistics for data shown in Figure 7. The data were classified in 4 different E_{dyn} ranges. Occurrences refers to the number of times a value lay within a given range. Additionally, they can also be interpreted as a probability, since the number of occurrences was divided by the total number of samples for each case. By looking at these results as a forecast tool, the probability of using a given type of rock support can be deviated from seismic results of future campaigns. For instance, if a campaign is done at the EP and along 50 m within the prediction range, Edyn values are between 30 and 40 GPa, the chance of applying rock support type 3 along this section is 83%. Moreover, inferences about the expected deformation can also be done, in this case, the minimum and maximum D_{acc} will be about 1.3 and 5.3 cm, respectively.

Table 3. Statistical analysis for the Entry Portal. Occurrence is expressed in percentage, Mean D_{acc} is in cm. Highest value for each group are highlighted in light blue and yellow, respectively.

			Rock Support (occurrence)			
E_{dyn}	Occurrence	Mean D_{acc}	2	3	4	5
20-30	27	12.96 ± 6.44	0	10	77	13
30-40	11	3.27 ± 1.99	0	83	17	0
40-50	45	6.90 ± 1.00	16	65	12	8
>50	20	4.54 ± 2.37*	60	35	5	0

*One sample (outlier) was not included in this calculation

Table 4. Statistical analysis of data shown in Figure 7 for the Exit Portal. Occurrence is expressed in percentage, Mean D_{acc} is in cm. Highest value for each group are highlighted in light blue and yellow, respectively.

			Rock Support (occurrence)			
E_{dyn}	Occurrence	Mean Dacc	2	3	4	5
20-30	39	21.45 ± 11.09	0	0	59	41
30-40	33	15.27 ± 10.74	0	52	48	0
40-50	28	9.41 ± 7.30	0	85	15	0
>50	0	0.00 ± 0.00	0	0	0	0

6. Conclusion

The TSP results and their comparison with the excavated geology and the estimated RMR values allowed for a detailed validation of the seismic results. In general, the seismic predictions matched very well the rock mass condition experienced while excavation. The seismic method proved its accuracy and benefit to the job site showing that it is an efficient and reliable tool to obtain geological information up to 150 m or more ahead of the face. Furthermore, by analysing data from different sources, such as geological information, rock classification and convergence measurements, additional useful information was obtained, which greatly supports the decision-making process for the appropriate support class during tunnelling.

A positive correlation between the parameters obtained from the in-situ seismic measurements and convergences was found, despite the transient nature of the tunnel deformation near the face. This important finding needs to be further studied and corroborated by performing similar evaluations in other job sites. Such reference works can be used as a tool for the interpretation of seismic data. They contribute to a more detailed prediction that includes information about the expected deformation and the rock support to be used. In addition, the reliability of the information obtained from the deformation-elastic modulus graphs is likely to increase considerably with the integration of further data to be collected. The results presented in this work were further employed for the following seismic measurements performed at the project. More than 60 seismic campaigns were performed. The tunnel excavation was completed in 2023.

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References

Apoji, D., Sheil, B., Soga, K., 2023. Shaping the future of tunneling with data and emerging technologies. Data-Centric Engineering, 4 (e29). https://doi.org/10.1017/dce.2023.24

Dickmann, T., Krueger, D., 2014. How to turn geological uncertainty into manageable risk? Proceedings of the World Tunnel Congress 2014 – Tunnels for a better Life, Foz do Iguaçu, Brazil.

Kim, C.Y., Kim, K.Y., Baek, S.H., Hong, S.W., Bae, G.J., Lee, S.H., Schubert, W., Grossauer, K., Lee, Y.Z., 2005. Tunnel convergence analyses in heterogeneous/anisotropic rock masses. In Underground Space Use – Analysis of the Past and Lessons for the Future, Volume 2, pp. 1091–1097. Proceeding of the World Tunnel Congress 2005, Istanbul, Turkey.

Kontogianni, V., Stiros, S., 2003. Tunnel monitoring during the excavation phase: 3-D kinematic analysis based on geodetic data. Proceedings of the 11th FIG Symposium on Deformation Measurements, Santorini, Greece.